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# NATIONAL BUREAU OF STANDARDS REPORT

3483

## ANALYSIS OF TOOL HEATING PROBLEM

By

William F. Roeser

To

Materials Division  
Structures Research Department  
U. S. Naval Civil Engineering Research & Development Laboratory  
Construction Battalion Center  
Port Hueneme, California



U. S. DEPARTMENT OF COMMERCE  
NATIONAL BUREAU OF STANDARDS

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# ANALYSIS OF TOOL HEATING PROBLEM

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## 1. INTRODUCTION

Our ideas of hotness and coldness are fundamentally derived from our sensations; and though, in some instances, we may have cause to distrust the information which we obtain through these channels, it does not follow that we should, even were it possible, discard entirely these foundations for our knowledge of the phenomena connected with the tool heating problem. For example, if various objects in a room are touched successively, it will be found that the metal objects feel cooler than the other objects, even though they are all at essentially the same temperature. The reason for this is that the sense of touch does not inform us directly of the temperature of an object, but of the rate at which an area of our skin gains or loses heat. Thus to control the hotness or coldness of metallic objects we must seek means of controlling the rate of heat exchange between the object and the sensitive portion of the skin.

Although we are not able to give an exact solution because of uncertainties in effects due to callous skin, perspiration, contact pressure, etc., we can give some of the more important factors that govern the rate of heat transfer.



## 2. TOOLS WITH SOLID HANDLES OF ONE MATERIAL

Assume that we have two semi-infinite solids A and B at uniform temperatures  $T_A$  and  $T_B$ , respectively. Let  $C_A$ ,  $P_A$ , and  $K_A$  be the heat capacity per unit mass, the density, and the thermal conductivity, respectively, of material A; and  $C_B$ ,  $P_B$ , and  $K_B$  be the values for the corresponding properties of material B. (Any set of units may be used, provided they are consistent.)

It can be shown mathematically that, if these two bodies are suddenly brought into intimate thermal contact, the temperature ( $T_S$ ) of the interface is given by

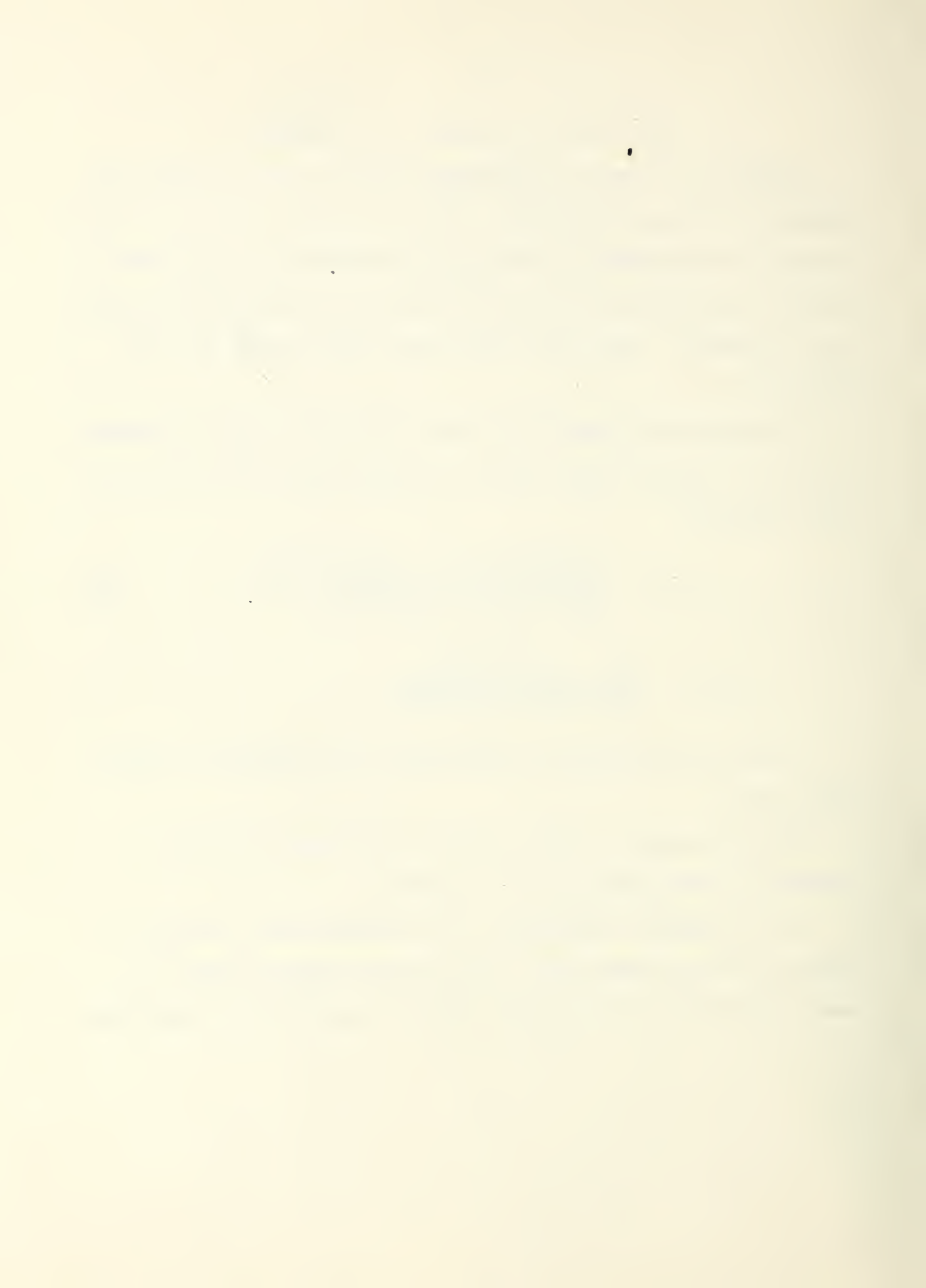
$$T_S = \frac{T_B \sqrt{C_B P_B K_B} + T_A \sqrt{C_A P_A K_A}}{\sqrt{C_B P_B K_B} + \sqrt{C_A P_A K_A}} \quad (1)$$

$$= T_B + \frac{(T_A - T_B) \sqrt{C_A P_A K_A}}{\sqrt{C_B P_B K_B} + \sqrt{C_A P_A K_A}}$$

It should be noted that the temperature of the interface is independent of time.

The above problem is given in Section 42 of "Modern Operational Mathematics in Engineering" by R. V. Churchill.

In the handling of implements, we are concerned with a material of finite size and the human hand. It is true that neither of these is a semi-infinite solid, but for short periods of time they may be considered





as such. Thus, if an implement with a handle of material A at a uniform temperature  $T_A$  is firmly gripped by the hand (material B), the temperature of the surface of the skin will come to a temperature  $T_S$ .

The rate of heat transfer from the surface of the skin to the temperature and pain receptors below the skin should be very closely proportional to  $(T_S - T_B)$ .

A few simple experiments were made to determine if the above relationship held, approximately, for the gripping of implements of different materials with the hand. The implements were heated in an oven to various temperatures, and the maximum temperatures at which two observers agreed that they could handle them without undue discomfort were established. These values are given in the second column of the following table. The third column gives approximate values of the ratio

$$\frac{\sqrt{C_A P_A K_A}}{\sqrt{C_B P_B K_B} + \sqrt{C_A P_A K_A}} = R$$

for the different materials and the fourth column gives the calculated values of the skin temperature.

Material	$T_A$ °F	R.	Skin Temp. °F
Carbon Steel	119	0.89	116.8
Plastic (Used for tool handles)	158	0.30	116.4
" " " " "	160	0.29	116.4
Hardwood (sp.gr. = 0.82)	169	0.24	115.5
Softwood (sp.gr. = 0.5)	183	0.16	112.1
Considered average			116.



In the above calculations,  $T_B$  was taken as  $98.6^{\circ}\text{F}$ , and the values of  $C_B$ ,  $P_B$ , and  $K_B$  for the body were taken to be the same as those of water.

Even though the temperatures of the implement handles ranged from  $119^{\circ}$  to  $183^{\circ}\text{F}$ , the temperature of the skin came to approximately the same value in each instance, indicating that the rate of heat transfer was nearly the same in each case.

According to the above relationship, the human tongue should stick to steel at any temperature below  $23.8^{\circ}\text{F}$ .

Equation (1) can be rearranged to read

$$T_A = T_S + \frac{(T_S - T_B) \sqrt{C_B P_B K_B}}{\sqrt{C_A P_A K_A}} \quad (2)$$

Substituting for  $T_S$ ,  $116^{\circ}$ , the maximum temperature of the surface of the skin that can be tolerated and for  $T_B$ ,  $C_B$ ,  $P_B$ , and  $K_B$ , the values for the body, we have

$$T_A = 116 + \frac{0.66}{\sqrt{C_A P_A K_A}} \quad (3)$$

where  $T_A$  is in  $^{\circ}\text{F}$  and  $C_A$ ,  $P_A$ , and  $K_A$  are in Cal, Cm, Gram,  $^{\circ}\text{C}$  and Sec units.

This equation gives the maximum temperature,  $T_A$ , at which an implement can be handled in terms of  $C_A$ ,  $P_A$ , and  $K_A$ .

Even though the above relationship is based upon the assumption that the two bodies considered are semi-infinite solids (which they are not), and even though no account was taken of the amount of moisture or



callousness of the hands, it gives a basis for the selection of materials which we believe to be in general agreement with experience.

### 3. TOOLS WITH COATED HANDLES

With different thicknesses of clear coatings of Plastisol R-2101 (a vinyl chloride) on steel rods, we found that the maximum temperature at which the coated rods could be handled varied with the thickness as shown in Figure 1. Apparently a 1/16-inch coating was just as effective as one of infinite thickness.

We can now set up the following relationship for steady-state heat transfer

$$q/a = \frac{K (T - T_s)}{D} = \frac{K_A (T_A - T_s)}{D_A} \quad (4)$$

where  $q/a$  is the heat transfer per unit area from a steel rod, through a coating, and to the skin,  $K$  and  $K_A$  are the thermal conductivities of the plastisol used and of any similar material that might be used, respectively, and  $D$  and  $D_A$  are the corresponding minimum thicknesses of coating that will permit the implement to be handled at the maximum tolerable temperatures of  $T$  and  $T_A$ , respectively. Substituting the known values for  $K$ ,  $T$ ,  $T_s$ , and  $D$  in equation (4), we have

$$\frac{0.11 D_A \text{ (in cm)}}{K_A} = (T_A - T_s) \quad (5)$$

From equation (3)

$$T_A - T_s = \frac{0.66}{\sqrt{C_A P_A K_A}} \quad (6)$$



<sup>5</sup>  
 $\frac{1}{2}$ " STEEL RODS COATED WITH PLASTICOL R-2101

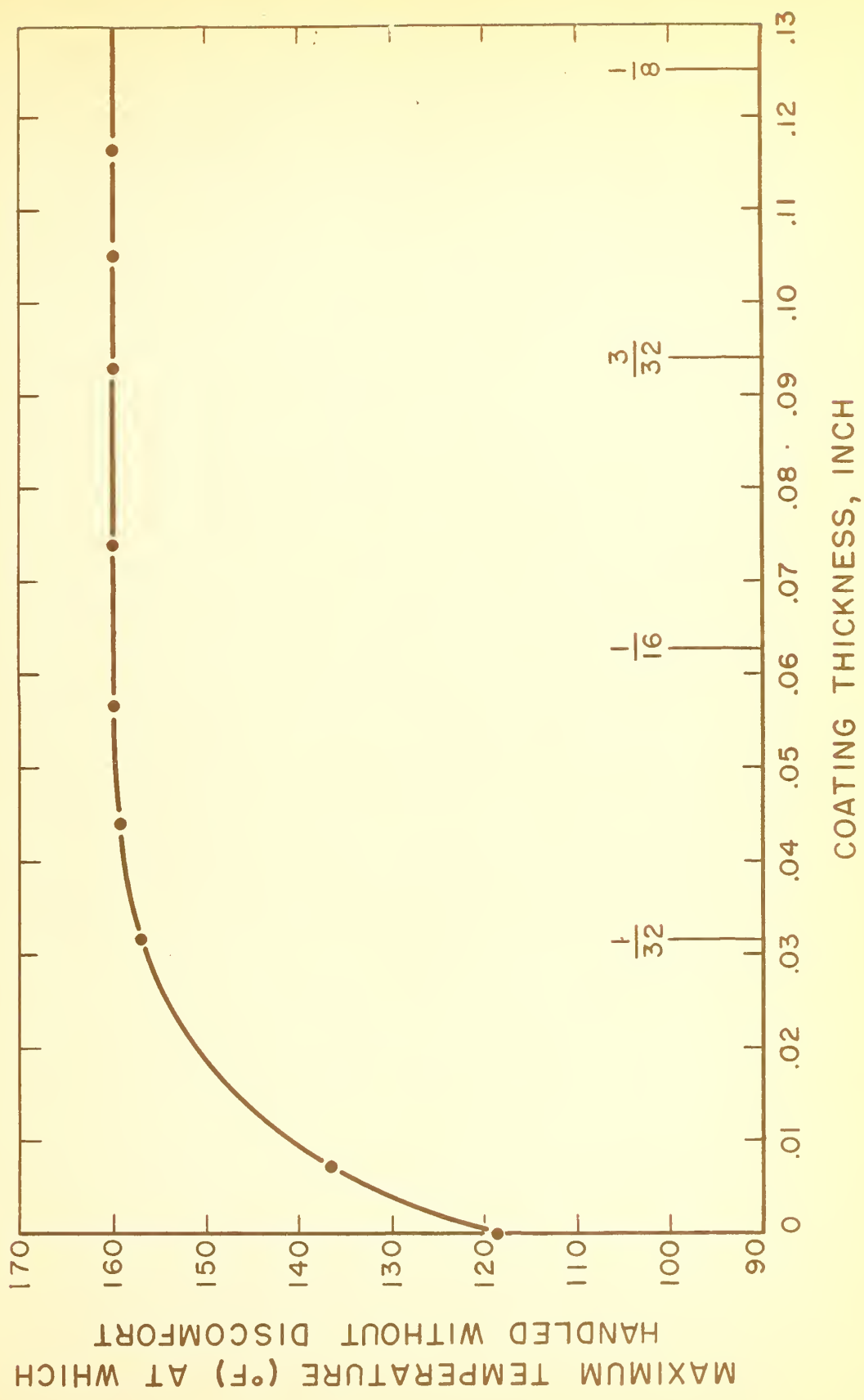


FIG. 1





Eliminating  $(T_A - T_S)$  and collecting terms, we have

$$D_A \text{ (in cm)} = 6.0 \sqrt{\frac{K_A}{C_A P_A}} \quad (7)$$

$$D_A \text{ (in inches)} = 2.36 \sqrt{\frac{K_A}{C_A P_A}} \quad (8)$$

$(C_A, P_A, \& K_A \text{ in Cal., Cm, G, } ^\circ\text{C, Sec})$

It is seen from equations (6) and (8) that any reduction in the values of  $C_A$  and  $P_A$  of the coating material will increase both the maximum temperature at which the implement can be handled and the minimum thickness necessary to permit the implement to be handled at the maximum temperature. As an example, if  $K_A$  is maintained constant and the product,  $C_A P_A$ , reduced by a factor of 4, both  $(T_A - T_S)$  and  $D_A$  are increased by a factor of 2. Any reduction in the value of  $K_A$  will increase the maximum temperature at which the implement can be handled and will decrease the minimum thickness of the coating necessary to permit the implement to be handled at the maximum temperature. As an example, if  $C_A$  and  $P_A$  are maintained constant and  $K_A$  reduced by a factor of 4,  $(T_A - T_S)$  is increased by a factor of 2 and  $D_A$  is decreased by a factor of 2. All this means is that the rate of heat transfer through the coating ( $q/a$  in equation (4)) has been maintained constant.

The maximum temperature,  $160^\circ\text{F}$ , at which we could handle the plastics used in our experiments is so near the temperatures that tool handles might



attain when exposed to the sun that consideration should be given to any means of reducing their temperature. In some experiments which we made in the period June 22, to July 1, 1954, 1/2-inch steel rods coated with 1/16 inch of plastic and painted black attained a temperature of 60°F above the ambient, 90°F, when exposed to the sun. Under the same conditions, similar specimens painted white attained a temperature of 42.5°F above the ambient, while those without any paint attained a temperature of 57.5°F above the ambient.

The maximum temperature rise attained by any of the specimens was that of the one with a plastic coating painted black. If we express this temperature rise as 100 per cent, the following table gives the corresponding increase in temperature of other specimens exposed under similar conditions. All the temperatures measured were that of 1/2-inch steel rods to which the coatings were applied.

<u>Coating</u>	<u>Relative Temperature Rise Above Ambient, Expressed in Per Cent</u>
1/16 in. plastic, painted black	100
No plastic, painted black	97.5
1/16 in. clear plastic, no paint	96
None, cleaned	95
1/16 in. plastic, painted white	71
No plastic, painted white	69



From these data, it would appear advisable to consider adding a white filler to the plastic. This would not only aid in keeping the handle cooler, but also should reduce the cost of the plastic coating as well as making it more stable. We believe that the use of metallic powders as a filler should be avoided, since these would probably increase the conductivity of the coating material and would not aid in keeping the handle cool.

In the selection of a plastic with the desired thermal characteristics, such properties as the resistance to abrasion, greases, cleaning solvents, etc., should not be overlooked.

If any use is made of the above analysis, it is hoped that the limitations of the mathematical analysis due to assumptions involved and of the results based upon only a few simple experiments, are borne in mind. If they are not, someone might get his fingers burnt, literally.



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Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards (\$1.00). Information on calibration services and fees can be found in NBS Circular 483, Testing by the National Bureau of Standards (25 cents). Both are available from the Government Printing Office. Inquiries regarding the Bureau's reports and publications should be addressed to the Office of Scientific Publications, National Bureau of Standards, Washington 25, D. C.

